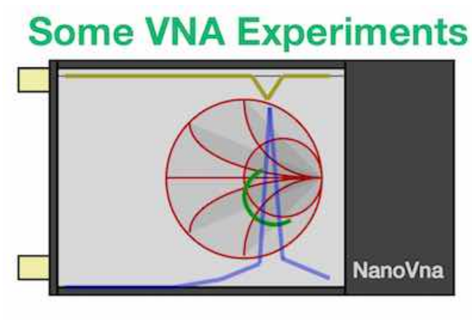

Evaluating the NanoVNA

Wes Hayward, w7zoi written15 Jan 20, 27Feb20, 3Mar20, 11Sept20

It all started during the Holidays when our son Roger showed us his new NanoVNA vector network analyzer. I was so impressed that I placed an order for one of my own a day or two later.

I already had a VNA in my lab, one designed by Paul, N2PK. Paul had built what I believe was the first direct conversion vector network analyzer. It used a DDS architecture with MC1496 mixers. The processing was done in a computer attached to the hardware. The performance was outstanding up to the 60 MHz top frequency with a dynamic range that equaled or exceeded that of some commercially available high performance VNAs. This analyzer was never published in the literature, but was treated extensively on line in a Yahoo-Group site. (**Many thanks to Paul, and many other group members for some wonderful work**.)

The photos shown below illustrate some of the performance of my new NanoVNA and, in some cases, comparison with the N2PK instrument. **(Figure captions use bold blue text.)** This report is aimed at experimenters already familiar with **vector** network analysis, much more powerful than sweepers or scalar analyzers.

Bandpass Filter Measurements

We begin this investigation with a difficult measurement. In some applications I had seen a spectacular dynamic range of over 100 dB with the N2PK and wondered how the Nano would do when testing filters. The scheme used is shown below.

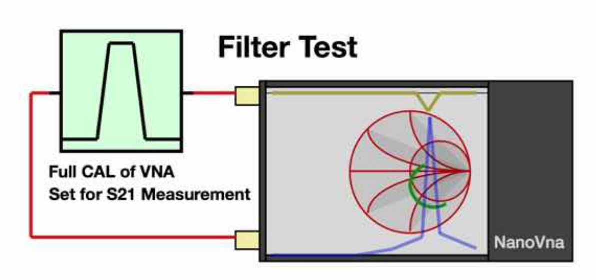

Fig 1. The fixture for a filter test.

The first experiment compares a N2PK analysis of a **crystal filter** with the same filter measured with the NanoVNA. This filter has a bandwidth of 2.4 kHz. The circuit was designed for a 0.1 dB ripple Chebyshev filter shape. The filter uses 8 crystals at 11.06 MHz and was intended for use in a SSB transceiver.

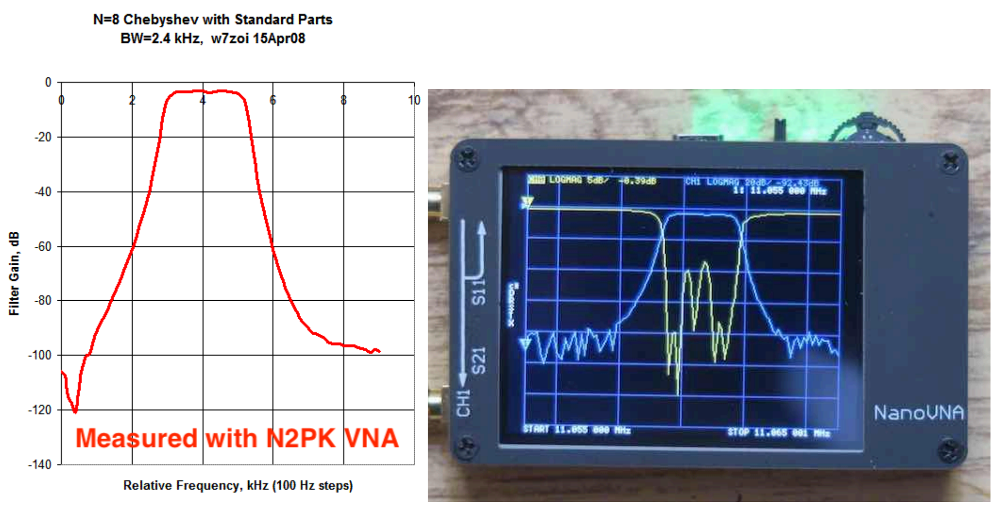

Fig 2. A crystal filter is first examined with the N2PK (left) and then the NanoVNA. The Nano is set up for 20 dB/div for the blue S21 response and 5 dB/div for the yellow S11 response. The Nano seems to lack stop band performance once the response is 80 dB down. That said, 80 dB is better than expected. The NanoVNA measurements were done with the short cables supplied with the Nano while the N2PK measurement used double shielded cables.

The NanoVNA was calibrated for 11.05 to 11.07 MHz. After the first run with this, the frequency sweep was changed to 11.055 to11.065 without a new calibration. The NanoVNA was calibrated with the "standards" supplied with the unit. Since the initial measurement, I have built a new 50 ohm calibration load consisting of a SMA male connector with two 0.1 % 100 Ohm 0805 SMA resistors.

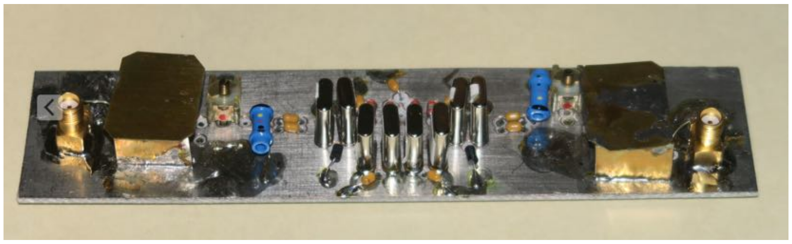

Fig 3. This photo shows the crystal filter. The shields cover toroids used to transform the filter end impedance values to 50 ohms. Without the shielding, the stop band attenuation was compromised.   Even toroids have a little bit of leakage. The 11 MHz HC-49 crystals came from a sack purchased at a local industrial surplus outlet.   The filter was designed with XLAD, a program distributed with EMRFD. (Hayward, Campbell, and Larkin, Experimental Methods in RF Design, ARRL, 2003)

The next experiment evaluated an LC bandpass filter.   This is an easier measurement than that of the crystal filter. A photo of the LC filter is shown below.

Fig 4. This filter has a 14 MHz center frequency with a bandwidth of 0.4 MHz. The fixed capacitors are very old style "dog bone" types from my junk box, originally from the Tektronix company store.   These dog bone capacitors s have excellent NP0 temperature stability and high Q.

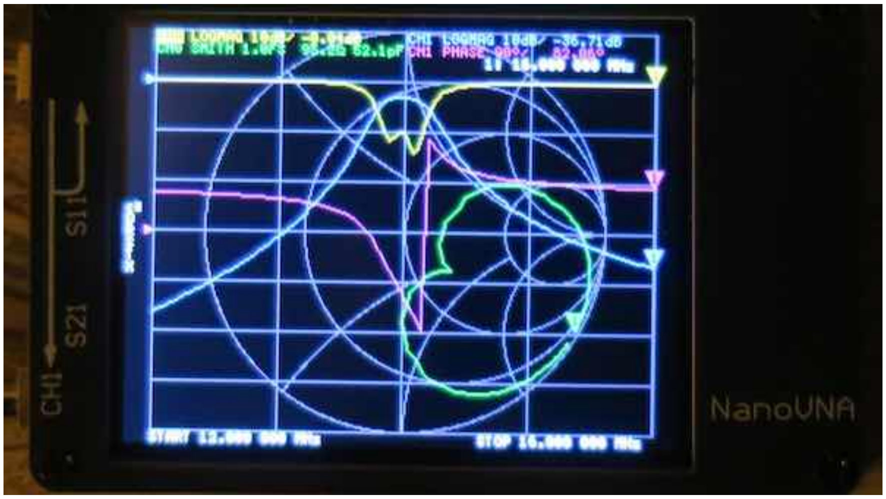

Fig 5. Above is the Nano VNA response for the LC double tuned circuit. S21, the forward response, is in blue. The insertion loss of about 3 dB is clearly evident. |S11|, the input match magnitude, is in yellow while the detailed frequency dependent input impedance, a Smith Chart, is in green.

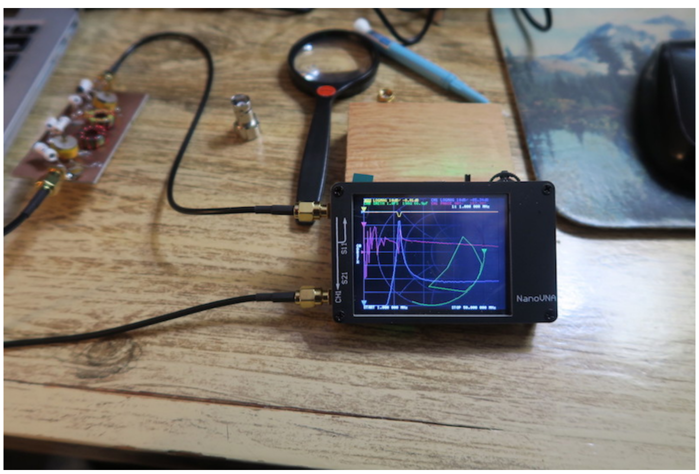

Fig 6. This photo shows the VNA, the LC filter under test, and additional table sweepings. The magnifying glass attests to the small size of the NanoVNA! The first sweep used a CAL from 1 to 50 MHz. As expected, the Smith Chart trace in green only has a few points that are *NOT* on the edge of the chart. The double tuned circuit used series capacitors from the resonators to the 50 ohm ends and a capacitor between resonators.

Crystal Transfer Function Measurements

The next analysis continues with the bandpass filter theme, but the filter is now merely a series crystal.

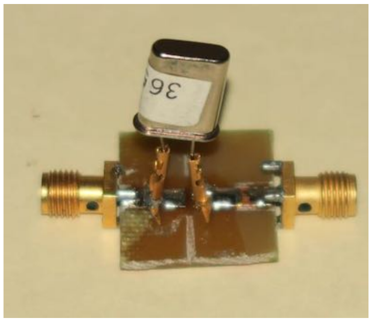

Fig 7. A test fixture where leaded HC-49 crystals can be inserted in a 50 ohm microstrip transmission line. This board will be used in other measurements later in this report.

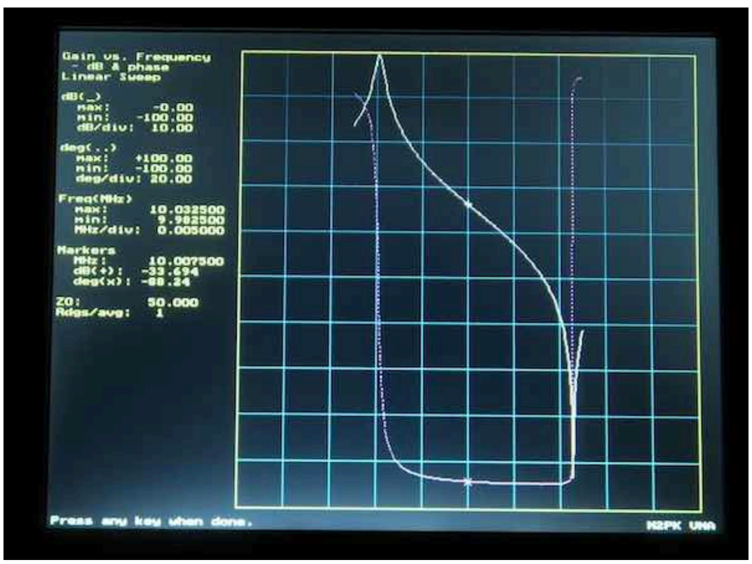

Fig 8.   N2PK VNA S21 sweep of the 10 MHz crystal of Fig 7.   An analysis routine from N2PK, "xtal2.exe", was used to characterize this crystal before the sweeps were done.   The crystal had Qu=280K.   Lm was 19.47 mH and C0 was 3.57 pF. Similar results for Lm and series F were obtained with the G3UUR measurement methods described in EMRFD.

Fig 9. NanoVNA sweep of the same crystal.

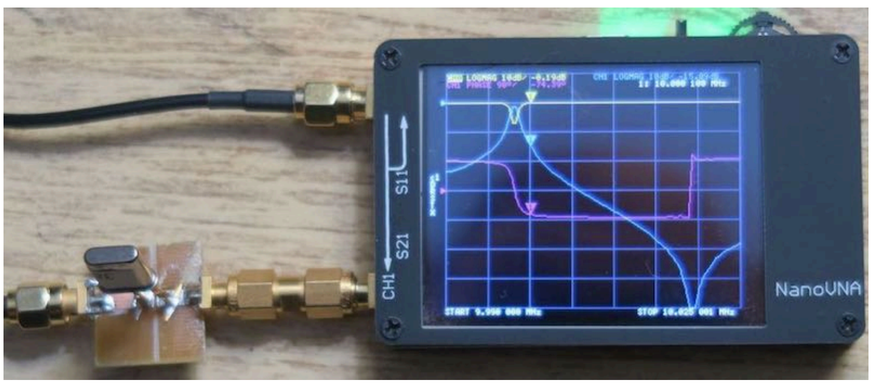

Fig 10. The 10 MHz crystal being tested with the NanoVNA.

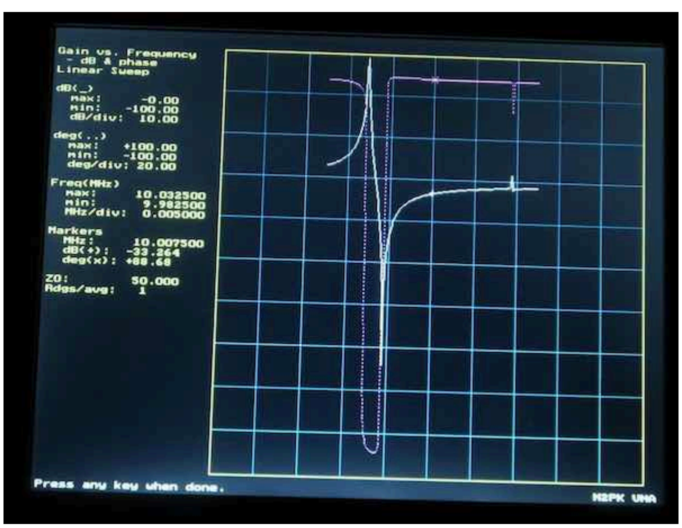

Fig 11. Above is a N2PK sweep of an very high Q crystal. This is a third overtone, glass packaged 10 MHz unit with unloaded Q of about 750,000. (Yes, Q really was that high.)

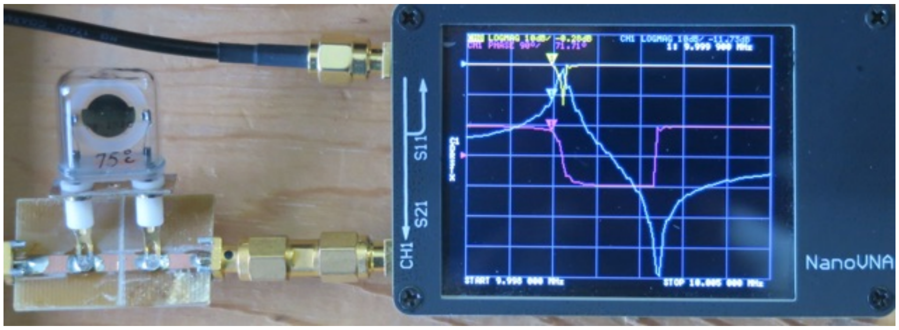

Fig 12. The high Q third overtone crystal and the resulting sweep with the NanoVNA. The fine structure observed near the peak is attributed to the VNA and not the crystal. The available power from the VNA for this measurement was approximately -8 dBm.

Antenna Measurements

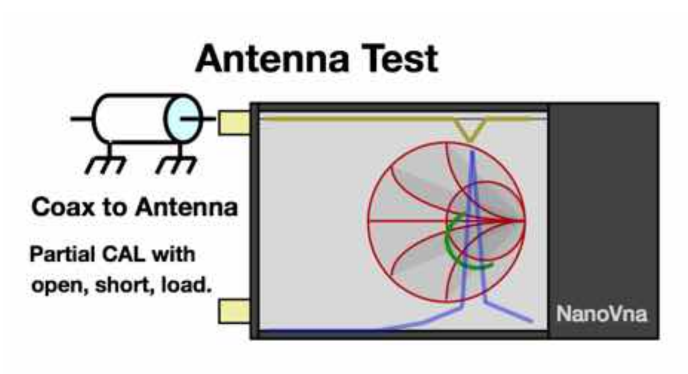

Fig 13. The NanoVNA may be used to examine an antenna.

Perhaps the most common application of a network analyzer in the amateur radio community is in the examination of impedances related to antennas. The following are examinations of my home antennas. The sweep is linear from 6 to 30 MHz.

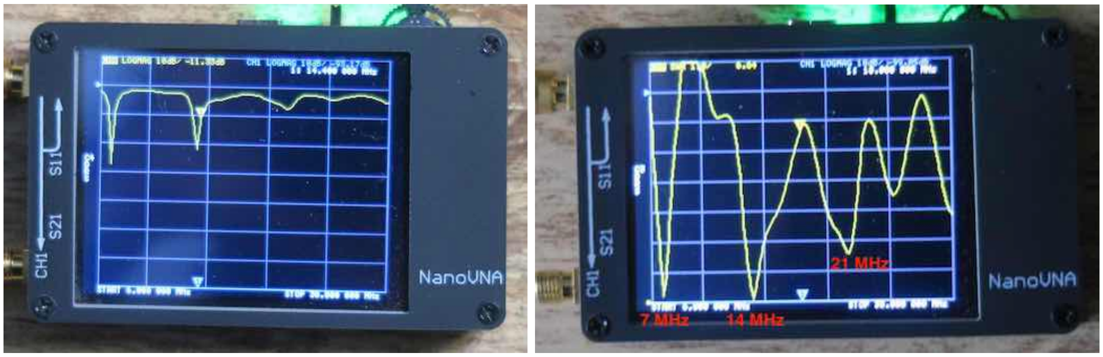

Fig 14. The left response shows S11 for a fan dipole. This antenna is a pair of Inverted Vee dipoles for 14 and 7 MHz on a single feed line with a common mode choke balun at the feed point. The right hand plot is exactly the same data except that the SWR VNA option was picked rather than S11. This plot is annotated (in red) with the frequencies where the match approaches 1:1. SWR is typical of the mode that will be used in most ham shacks.

Some folks refer to the left hand response as *return loss*. **This is not formally correct**. Return loss values are positive numbers while S11 values for passive circuits are negative. A VNA measurement producing a S11 value of, for example, -12 dB will have a return loss of +12 dB.

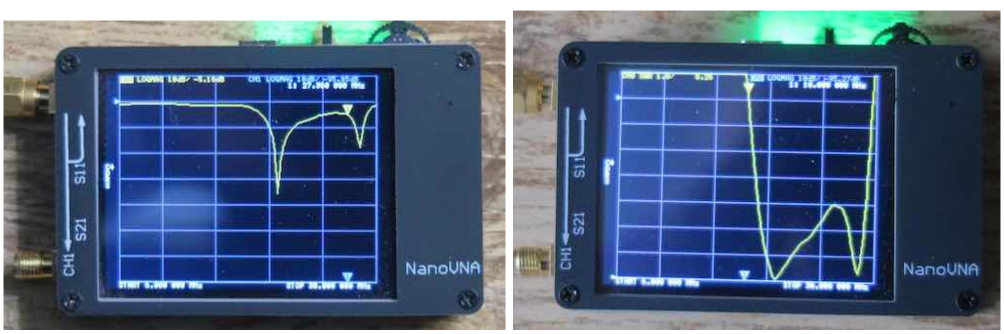

Fig 15. This is an analysis of a different antenna, a 21 MHz dipole that has a 28 MHz element parallel to it and spaced at about 8 inches. These dipoles are made from aluminum tubing and can be rotated. Only the 15 meter dipole has an attached feed line with a common mode choke balun. As in the previous figure, the left is an S11 plot while that on the right shows SWR. The 35 dB *return loss* in the left photo corresponds to the near 1:1 *SWR* at 21 MHz on the right.

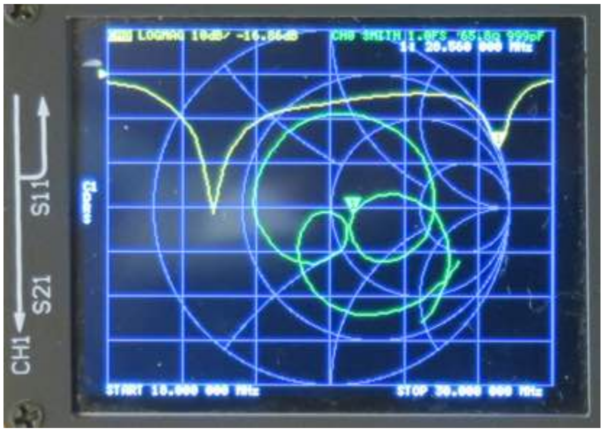

Fig 16. Another antenna sweep with the same antenna. The sweep range is 18 to 30 MHz, offering more frequency resolution. This figure shows the magnitude of S11 (rather than SWR) and the Smith Chart. The Smith Chart emphasizes the *vector* nature of the measurement. This also illustrates an educational virtue of the VNA: By observing the S11 plot and the Smith Chart while moving the cursor about, the viewer may well become more comfortable with the Smith Chart. (It really is a useful thing.)

A subtle detail emerges with careful examination of the above plot. The readout data in the upper right corner of the screen shows the cursor frequency (white) and the corresponding impedance (green.) However, the impedance form is not really the complex number that we might expect. Rather, it's the resistance followed by the equivalent circuit element at the specified frequency. In this case, at F=28.56 MHz the resistance is 65.8 ohms, and the displayed reactive element is specified as 999 pF. That is, the impedance looks like a capacitor, but one with **large** value that has corresponding **low** reactance. The vector impedance is 65.8 -j5.6 ohms. Both forms are fine. (I'm not sure which I prefer.)

Inductor Q Measurement

A common measurement performed with a VNA is that of Q. Low Q inductors can often be directly measured, for the low Q means that the equivalent series resistance (ESR) is high and is close to the reactance value. The inductor is merely attached to the Tx port and the complex impedance is measured. As Q become higher, the ESR drops while the reactance does not, making measurement more difficult. A solution is to resonate or *tune* the reactance as shown in Fig 17. This measurement happens to use a transmission mode, but an impedance measurement can yield the similar results. If it is desired to measure the Q of an inductor, a high quality capacitor is attached to the inductor, effectively cancelling the inductive reactance, leaving only the ESR to be measured.

We can then calculate resonator Q.

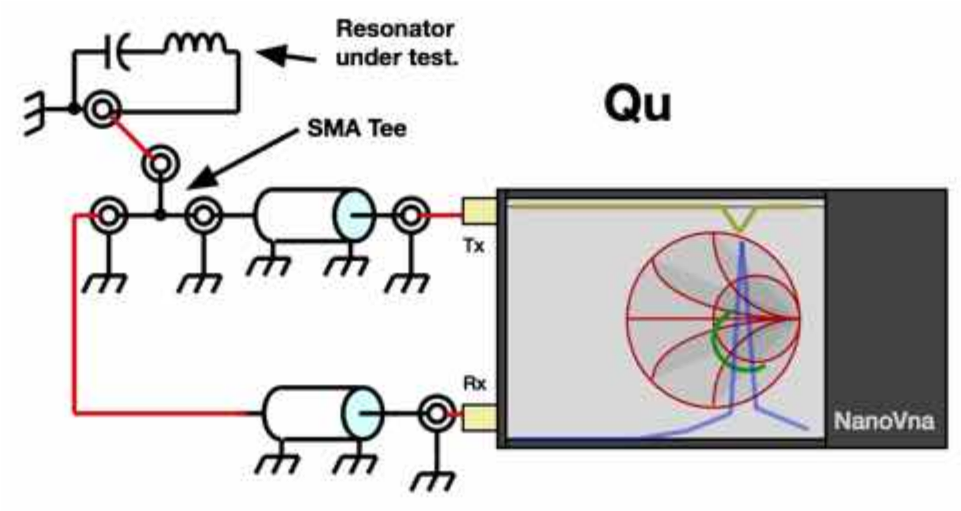

Fig 17.

Measurement of resonator Q.

Traditionally, we assumed that the capacitor was very good and that measurement losses were those of the inductor. This assumption has changed. Toroids often have relatively high Q. Tuning capacitors have a less than perfect Q, especially with many SMT parts. This is discussed in more detail on the web at http://w7zoi.net/twofaces.pdf .

Figure 17 above shows us how Q can be measured. It is done with a network analyzer operating in transmission mode. The resonator to be measured is attached as a shunt element. Without an attached LC, there is a direct path from the TX to the RX ports on the VNA. All of the available energy from the transmitter is available at the receiver. Hence, S21 is a straight line across the top of the display. The tuned circuit is then inserted in the in the circuit. The resonator is a short circuit from the path from the VNA TX port to the RX port. At resonance, the tuned circuit has zero reactance, leaving only the resistance as a path to ground. If the system is calibrated and the attenuation is measured at the bottom of the dip, the ESR and hence the Q can be calculated. See EMRFD, Eq. 7.4, page 7.37. This method can be used with a stable signal generator and a power meter, when a VNA is not available. Measurement accuracy depends upon a known source impedance.

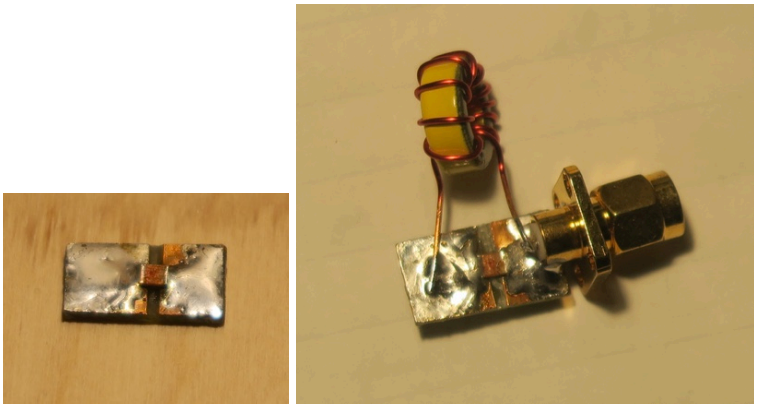

Fig 18.   The left photo shows a 100 pF high Q SMT mica capacitor mounted on a small board.   This is a CDE part number MC12FA101J-F.   This part is, at this writing, still available from Mouser, although it's expensive.   The right photo shows the board soldered to a SMA connector.   The inductor to be measured, 11 turns of #22 on a T50-6 toroid core, is connected between the capacitor and the coax center pin.

The measurement described here was done with a SMA Tee connector.   But those are not common parts.   A small circuit board like those shown in earlier measurements (Fig 7) would work as well.   I keep a 100 pF CDE capacitor permanently mounted on a small, high quality circuit board that can then be tack soldered to an inductor that is to be measured.   Short leads are always a good idea, but are not so critical in the HF spectrum.

Fig 19.   This shows the result of the Q determination.   The resonant frequency of the LC was just over 21 MHz.   The inductor value was 0.549 uH.   The attenuation at the bottom of the dip was 37.9 dB, indicating a Q of 226.   Subsequent

measurement of that inductor on an HP4342A Q meter was Q=272. The difference indicates a capacitor Q of about 1300. (See http://w7zoi.net/twofaces.pdf.) The mica capacitor is specified to be a bit higher than this for Q. Circuit board loss may be a contributing factor. The output resistance of the Tx port is also a critical part of the measurement.

Crystal Q Measurement

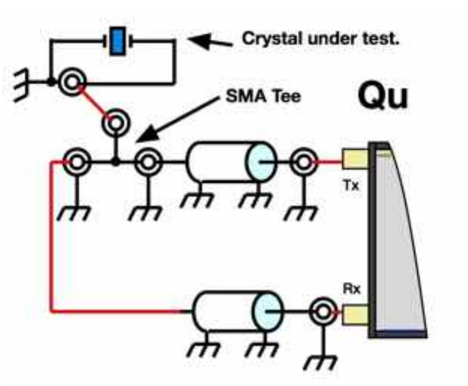

Fig 20. The VNA configuration used to measure crystal Q.

Crystals are NOT difficult to model. The equivalent circuit is just a series RLC which is paralleled by a small capacitance. The small parallel C is easily measured at a low frequency. Motional L and C, the series RLC parts, can then be measured with a crystal oscillator and frequency counter. See Fig 3.35 on page 3.19 of EMRFD for a discussion of the G3UUR method. This leaves determination of the ESR. The same method used to measure the Q of an inductor-capacitor combination can be applied directly to a crystal. The small parallel C mentioned can be ignored, for it is only a few pF and contributes little in a 50 ohm environment. All that's left is the crystal series RL_mC_m. The "m" subscripts indicate motional components.

The SMA Tee was again used for crystal measurements. The 10 MHz crystal was inserted in the same PC board used for earlier transmission measurements and that board was attached to the SMA Tee connector. The SHORT from the VNA Cal kit was placed on the other end of the small board. The VNA was calibrated from 9.99 to 10.01 MHz with a 1 dB/div vertical resolution. The first result shown below includes the test fixture.

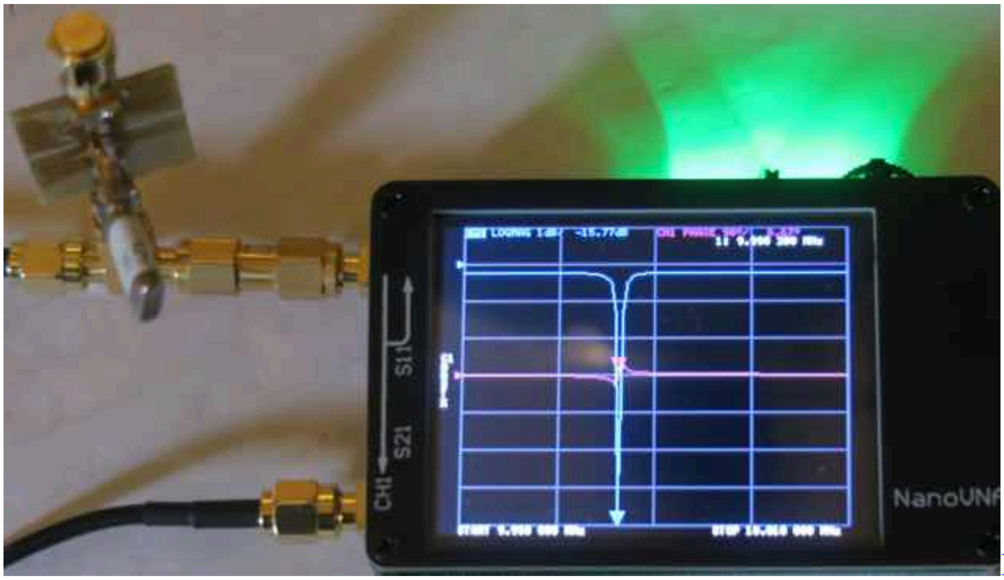

Fig 21. Measurement of the Q of a crystal.

The result was confusing with the NanoVNA. The vertical scale was set to 1 dB/div, the readout at the cursor showed S21 of -15.6 dB at 9.9982 MHz, well below the bottom of the screen. The frequency stimulus was then changed from a 20 kHz total span to 2 kHz with a more realistic vertical resolution of 5 dB/division with the result shown below.

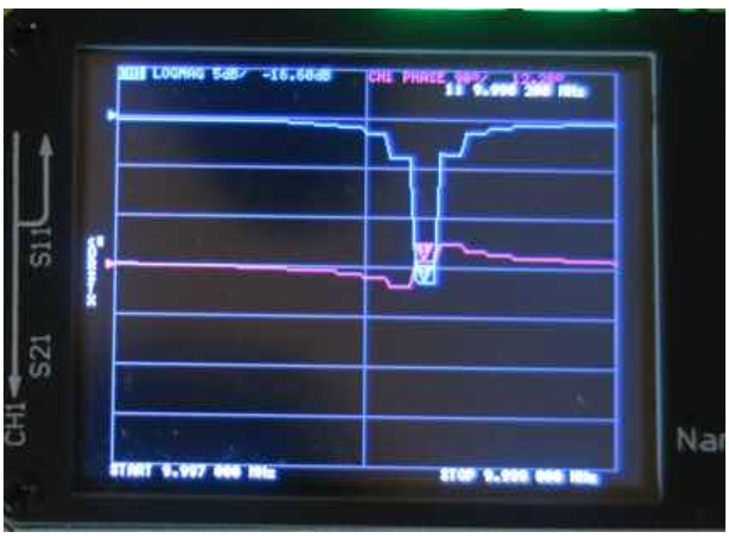

Fig 22. Measurement of the Q of a crystal, 2 kHz total span.

This trace shows a fine structure that we did not expect. It would appear from this trace that the internal software does not allow a frequency step less than 100 Hz. The attenuation was 16.6 dB for this case. In an attempt to look at the S21 dip response in even more detail, the total span was dropped to 500 Hz, 5 dB/div was retained, and a new CAL was done. This produced the sweep of Fig 23.

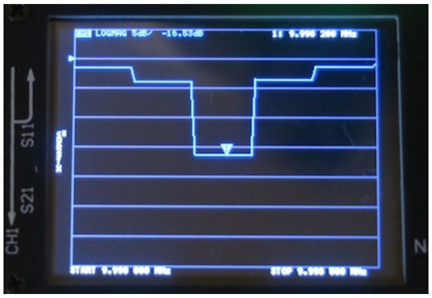

Fig 23. Crystal Q measurement, 500 Hz span.

Clearly, my version of the Nanovna with the software that was shipped with it will not allow the usual 100 points distributed over the total span called out in the CAL. If that had worked in this example, we would have had 5 Hz step size rather than the 100 Hz shown in Fig 23. The same measurement done with the N2PK VNA yields a clean sweep without the synthetic flat regions. The attenuation from the VNA of 16.5 dB, when combined with Lm from an earlier measurement yielded Q=279K (See caption for Fig 8.)

Conclusions

I generally like the NanoVNA. It's amazing what they were able to cram into such a small volume and equally astounding that the price is so low. The small size makes it handy for a lab that will eventually be reduced in size. That said, the small size make the VNA difficult to use. Further, some screen elements are too bright compared with others, making it difficult to read the numbers.